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The Gap Waveguide as a Metamaterial-based Electromagnetic Packaging Technology Enabling Integration of MMICs and Antennas up to THz

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***Abstract*— This paper presents new topics that will be lectured in the short course *Metamaterials for Antennas* within the European School of Antennas in Spring 2012. These relates to new so-called gap waveguides that are advantageous for use above 30 GHz, because they are quasi-TEM over wide bandwidth, and do neither require dielectric material nor conductive joints between metal parts. The gap waveguides originate from research on soft and hard surfaces that also are forerunners for EBG surfaces (acting as isotropic soft surfaces) and metamaterial cloaks (realized first by hard surfaces). The course will contain material related to all these topics, and in addition an overview of the last years research on the gap waveguides including experimental demonstration of principles as well as working hardware components. In this presentation special emphasis will be given to electromagnetic (EM) packaging, the principle of PMC packaging and integration of MMICs.**

I. Introduction

The European School of Antennas (ESoA) has a short course on Metamaterials for Antennas, which next time is planned for Spring 2012 at Chalmers University of Technology. This course gives an introduction mainly to artificial surfaces and their application in antennas, such as electromagnetic bandgap (EBG) surfaces, artificial magnetic conductors (AMC) [1], and soft and hard surfaces [2]. The latter represents ideally grids of Perfect Electric Conducting strips (PEC) and Perfect Magnetic Conducting strips (PMC) [3]. This research on artificial surfaces has resulted in new metamaterial-based waveguide types referred to as gap waveguides [4]-[7], appearing in the gap between parallel conducting plates. The gap waveguides appear in three variants: the ridge gap waveguide, the groove gap waveguide and the microstrip gap waveguide [6]. The demonstrator of the ridge gap waveguide is shown in Figure 1. The purpose of the present paper is to describe how these gap waveguides can be used as an electromagnetic (EM) packaging technology with potential of reaching THz.

The commercial success of an electronic product depends to a large degree on the technology used for electronic packaging. The construction set used for packaging determines in the very end the final production cost and quality. The packaging of integrated circuits (IC) involves steps such as die attaching, bonding and encapsulation. The present paper will focus on electromagnetic (EM) packaging, i.e. packaging in such a way that cavity resonances due to EM field modes are avoided at the same time as circuit performance is undisturbed or improved. EM packaging is a research field very suitable for antenna specialists. The present paper will explain the theoretical principles behind EM packaging, and it will propose a computational methodology to perform EM packaging referred to as PMC packaging [8]. Finally, it will present examples of how packaging has been done on practical high-frequency circuits using gap waveguide technology. The first example was published in 2009 [7], see also Figure 2, but now several more examples have been demonstrated.

The theoretical developments of the gap waveguides can be found in [9]-[11], and different ways of realizing the stopband in [12].

However, let us first define the term THz technologies as it is used in the present paper.

II. Extended Definition of THz technology

The THz band covers the wavelength range between 0.1 and 1 mm, and is therefore identical to the submillimeter wavelength band, according the Wikipedia, i.e. the frequency range 300 GHz to 3 THz. The microwave region is normally taken to be 3 GHz to 30 GHz, and the millimeter-wave range 30 GHz to 300 GHz. Still, it is normal to distinguish between microwave *frequencies* and microwave *technologies*, where microwave technologies are e.g. used as a name of distributed microstrip or waveguide technologies even when they are used far below 3 GHz or above 30 GHz. In the same way THz technologies can be used to denote new technologies that take over when microwave technologies become non-optimum, e.g. due to manufacturing problems or losses. The gap waveguide is such a technology [4]-[7], because its main advantages are above 30 GHz, and we believe up to THz frequencies, even though the demonstrators built so far are for frequencies below 20 GHz.

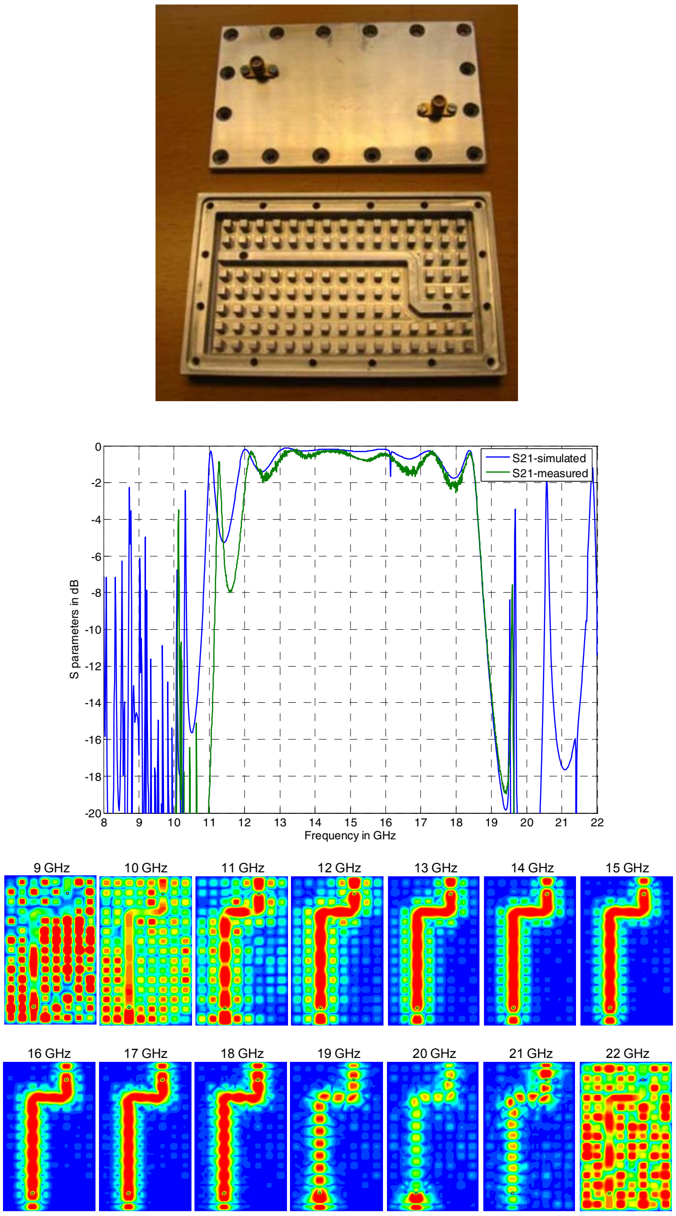

Figure 1. Performance of manufactured demonstrator of ridge gap waveguide with two 90 deg bends. Upper left: Photo of lower plate with texture in the form of a ridge and metal pins, and upper plate with two coaxial transitions. Upper right: Computed and measured S21 transmission coefficient between the two coaxial connectors when the upper plate is located at specified height over the texture of the lower plate. Lower: Colour plots showing field distribution between the plates at some specific frequencies. The gap wave can be observed between 11 and 20 GHz, and without a standing wave between 13 and 18 GHz.

The *THz gap* is normally a name used for paying attention to the fact that there is a lack of EM power sources at THz frequencies, thus there is a technology *gap* at THz frequencies. However, the THz gap can equally well be used to denote a lack of a lowloss cost-effective waveguide or transmission line technology in this frequency band. The gap waveguide may be able to fill this THz waveguide-technology gap.

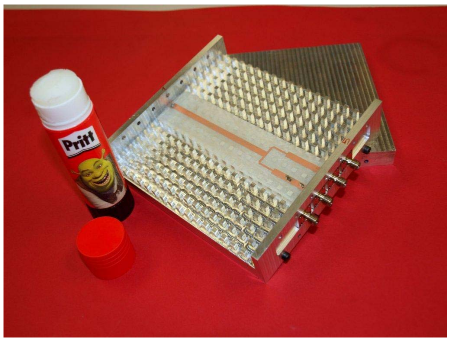

Figure 2. Suspended microstrip gap waveguide demonstrator from UPV. The ground plane of the microstrip line is in this case a smooth metal lid that shall be located above the microstrip lines shown. The lid "ground plane" I in the photo removed to reveal the microstrip circuit and the PMC realized by a bed of pins.

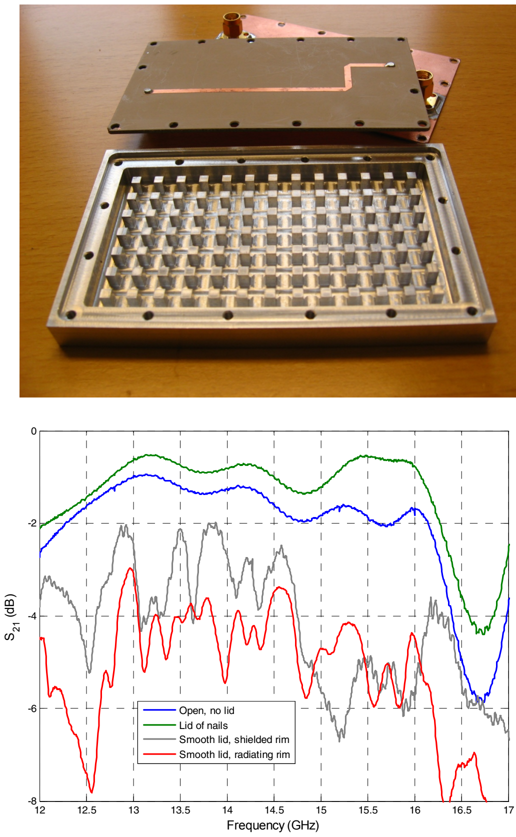

Figure 3. Hardware for demonstrating EM packaging of a microstrip circuit in the form of a microstrip line with two 90 deg bends. The packaging is done by a realization of a PMC in the form of a lid of nails. The transmission coefficient S21 is shown for different cases, and is best for the lid of nails [7].

III. EM PACKAGING: A NEW RESEARCH DISCIPLINE FOR ANTENNA SPECIALISTS

Electronic components and circuits need packaging for mechanical protection, and the packaging technology must at the same time provide conducting traces through the package walls. At microwave frequencies the packaging of components such as microstrip circuits become complicated, because the cavities inside the package become large and therefore will support cavity mode resonances that are devastating to performance. The resonances can be explained as electromagnetic modal solutions inside the cavity, which are known to appear when the volume has at least one diameter larger than half wavelength. At millimeter and submillimeter wavelengths such resonances may even appear within packaged monolithic microwave IC, i.e. MMIC, and these problems become even more profound when approaching THz. Therefore, there is a particular need for new construction architectures and methodologies that can be used to package RF circuits and MMICs above 30 GHz.

The EM package must in addition to suppressing cavity resonances, also provide input and output ports, and with advantage also integrated antennas, that allow RF (or IF or LF via ports) signals to enter and leave the module or package. Such ports and antennas, and the related transmission lines, can with advantage be part of the packaging technology itself. On this background it is natural to refer to such high-frequency packaging as electromagnetic (EM) packaging. EM packaging thereby becomes a new research discipline well suited for being explored by EM and antenna specialists.

IV. PMC Packaging: A Computational Pre-Packaging Approach

The gap waveguides were used in [7] (See Figure 2) to successfully demonstrate EM packaging of a microstrip line with bends, using a lid of nails. We have thereafter developed this practical packaging approach to a simple computationally oriented PMC pre-packaging approach.

Open microwave components, such as microstrip circuits, are usually designed without considering any package, i.e. as if they are located in free space, in spite of the fact that practical circuits need to be packaged, and then the packaging is solved afterwards and often by other engineers. The reason is that it is simpler to design open microstrip circuits than packaged ones, because the packaging adds complications due to the problems of cavity resonances, as previously explained. We have instead introduced a PMC packaging approach, in which the packaging is done from the start using a PMC lid [8].

The PMC packaging can be simply explained by reference to Figure 3. The PMC packaging is a numerical design approach. Step 1 is to design the microstrip circuit (or other open transmission line circuit) by using a PMC lid instead of assuming free space above the circuits. It is important that the lid is a PMC and not a PEC, because the PMC will stop parallel-plate modes to propagate between the two plates and cause resonances, provided the total height d between the PMC lid and the ground plane of the microstrip circuit is smaller than $\lambda_{eff}/4$ where λ_{eff} is the effective wavelength of the region. The PMC lid should also be located some distance above the circuit in order not to affect the characteristic impedance of the line (Figure 5). The PMC lid will reduce the computational volume and therefore also the computation time. It will also speed up convergence in moment method based microstrip circuit software. The second step is to realize the PMC lid using e.g. a bed of nails (Figure 4). In tis way the numerical design is done with packaging included, first by a computationally effective approach (PMC lid), and thereafter by a physical implementation of the PMC which is much more computationally demanding. The latter may require some retuning of the microstrip circuit.

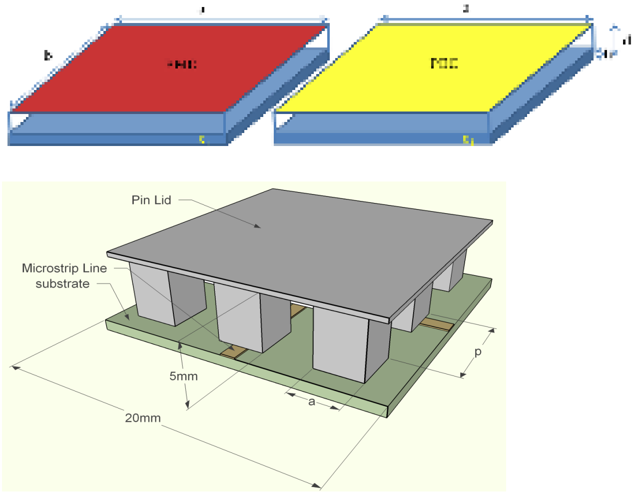

Figure 4. a) Geometry for modelling PMC and PEC packaged microstrip circuits. The PMC lid has several advantages. b) Realization of a PMC lid above a microstrip circuit by using a lid of pins.

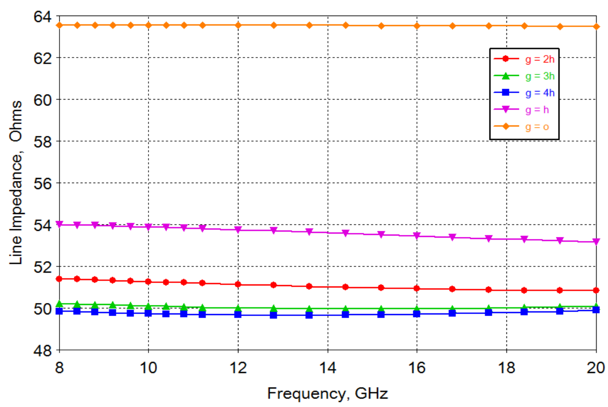

Figure 5. Computed change of characteristic impedance of a microstrip line due to a PMC lid at different heights. H is the substrate thickness.

V. Gap Waveguide Architecture for Integration of MMICs

There are many ways of integrating active components like MMICs in gap waveguides. At THz frequencies it is natural to realize the gap waveguides on the chip by micromachining, together with the semiconductor components. Below 100 GHz the chips may be mounted into architecture of gap waveguide components. Then, there is a need for a transition from the chip transmission lines to the gap waveguide. There is a problem that commercial chips or packaged MMICs are not provided with ports that are suitable for connecting to gap waveguides. As an intermediate step we are developing ways of mounting microstrip circuit boards with packaged MMICs as part of ridge gap waveguide circuit architecture. Some examples and results will be presented orally.

VI. CONCLUSION

The paper has given an overview of research on gap waveguides, which will be included in the ESoA course on metamaterials for antennas at Chalmers in 2012. There is a lot of antenna research waiting to be started in this fascinating area, now when the different characteristics of the waveguide itself have been determined.

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